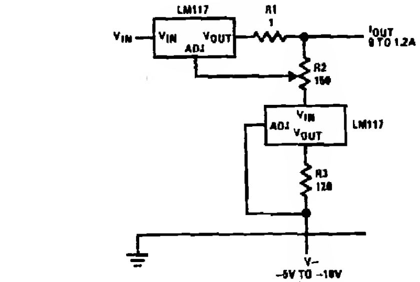

FIGURE 7. Adjustable Current Regulator

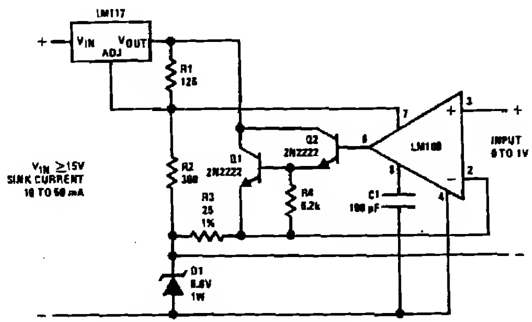

FIGURE 8. 10 mA to 50 mA 2-Wire Current Transmitter

RMS Converters and Their Applications

National Semiconductor
Application Note 180
John T. Lee
Hybrid Special Products

INTRODUCTION

A true RMS converter is a device which converts a signal (DC, AC, AC+DC) to its equivalent DC heating value. These devices are useful in fundamental measurements of virtually all waveforms.

SOME BASICS ABOUT RMS CONVERTERS

I. What is the RMS Value of a Waveform?

The Root Mean Squared (RMS) value of a waveform is a fundamental measurement of that waveform: it is a measure of the waveform's heating value when applied to a resistor.

A fundamental theory of Fourier Analysis states that any periodic function may be represented in a trigonometric series. This series is sum of sinusoidal components having different frequencies and amplitudes. These components are all multiples of the fundamental frequency. Thus, for a periodic function, the power content (also its mean-squared value) in the period T is defined to be:

$$\text{mean square value} = \frac{1}{T}\int_{-T/2}^{T/2} [f(t)]^2\,dt = \sum_{n=-\infty}^{\infty} |Cn|^2$$

where the Cns are the complex Fourier coefficients of the function. It is seen that if $f(t)$ is a voltage or a current waveform, then the mean square value represents the average power delivered by $f(t)$ to a 1Ω resistor. Summing its discrete components, one can obtain the power content of the signal. A graph of these components vs frequency is known as a power spectral density plot.

The RMS value is defined to be:

$$RMS = \sqrt{\frac{1}{T}\int_0^T [f(t)]^2\,dt}$$

Thus, one can see that the RMS value is just the square root of the mean square value.

Since the mean square value of a periodic function is the sum of the mean square value of its discrete harmonics (without regard to their phases) it is seen that any signal with the same mean square value (thus RMS value) will dissipate the same amount of energy, over a period, in a resistor.

Whereas periodic signals may be completely described by their amplitudes, phases, and frequencies, random signals are those where future behavior cannot be predicted. Random signals may only be described by quantities such as the RMS value, power spectral density, and probability distribution. If for a random signal there exists a statistical value such as the RMS that is independent of time, then this signal is said to be stationary. The RMS value of any stationary zero mean random signal is equal to the standard deviation of the signal.

Whereas periodic signals have a discrete power density spectrum, random signals have a continuous spectrum. The RMS value of a random signal may be defined to be:

$$RMS = \sqrt{\lim_{T \to \infty} \frac{1}{T}\int_0^T f(t)^2\,dt}$$

For a random signal, then, it is necessary to break the signal up into many narrow bands in order to investigate its power spectral density.

II. Why RMS Converters? Why Not Average Detect?

Since the mean square value (hence RMS) measures the power content of a signal, it provides a universal scale of measurement. An RMS measurement will give the intensity of a random phenomenon when averaged over a time interval. Besides periodic signals, phenomena such as acoustic noise, electrical noise, and mechanical vibration may be characterized. It is seen that instruments that read RMS values would be highly desirable.

Until recently, due to the high cost of RMS converters, most AC voltmeters did not read the RMS value of a waveform. Instead, they were average reading and RMS calibrated. This is done by taking the Mean Averaged Value (MAV) and multiplying by a factor of 1.11. This calibration is accurate only for measuring sinewaves. However, if the signal is not a pure sinewave, this type of instrument could lead to great errors. For example, such meters would read about 11% low on gaussian noise and about 11% high on symmetrical square waves. Note that if one knew beforehand that the waveform to be measured consisted of symmetrical square waves the meter could be calibrated accordingly. However, this meter would hardly be useful for anything else. Also, since many signals may change waveform during measurement, it would be impossible to try to calibrate the meter.

An example of a varying waveform would be the output of a ferroresonant line voltage regulator. The waveform could change from a sinewave to a square wave; when the output is a sinewave the average type meter would read correctly, however when the output is a square wave the meter would read in error of as much as 11%.

Another example would be the voltage from an SCR controlled circuit. An averaging meter would read correctly only during 180° conduction angle; it would read in error of 51% at 45° conduction angle.

Yet another example would be the output of an audio system during intermodulation testing. The true RMS value is insensitive to the ratio of frequencies, while the average value is highly sensitive to this ratio. Table I compares normalized readings between RMS and average detecting type meters. It is seen that whenever a waveform other than sinusoidal is to be measured, an RMS type meter should be used.

TABLE I. Comparison of RMS & AVG Detecting Type Meters

Waveform		RMS	AVG
Sine		1	1
SCR Cond Angle	180°	1	1
	90°	0.707	0.5
	45°	0.301	0.15
Gassian Noise		δ*	0.898*
Zero Based	10% duty cycle	$A/\sqrt{10}$	A/10
Pulse Train	1% duty cycle	A/10	A/100

* δ = standard deviation = RMS value

III. What Kinds of RMS Converters Are There?

There are basically three methods of RMS measurements:

1. **Thermal.** This method is achieved by converting an unknown voltage or current into heat in a known value of resistance.

2. **Direct Computing.** From the definition of RMS,

$$\text{RMS} = \sqrt{\frac{1}{T}\int_0^T f(t)^2\,dt}$$

we can see that the RMS value may be determined by first squaring the waveform, then averaging it, and then taking the square root. This method is illustrated in *Figure 1*.

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FIGURE 1. Direct Computing Type RMS Converter

3. **Implicit Computing.** This scheme is similar to the second one with the square root performed by feedback and the squaring done by log method. This method is illustrated in *Figure 2*.

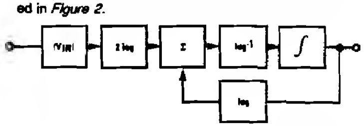

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FIGURE 2. Implicit Computing Type RMS Converter

Of the three methods mentioned above, the Implicit Computing method is by far the most desirable—since a converter of this type can achieve great accuracy, wide bandwidth, high dynamic range, and low cost. The LH0091, National Semiconductor's true RMS converter, is such a unit.

SPECIFICATIONS

An ideal RMS converter would have infinite crest factor response, infinite bandwidth, and no errors due to conversion. Since this is not yet an ideal world, the performance of a practical converter will be discussed.

A practical converter should have sufficient bandwidth to respond to the entire spectrum of the measured signal; it should also have adequate crest factor response and accuracy to meet the particular application. Thus, these are important characteristics of an RMS converter.

1. **Crest Factor.** Crest Factor is the peak signal value divided by the RMS value. In general, the higher the crest factor a signal has, the higher the conversion error will be for a converter. This is due to internal circuit limitations. However, most signals encountered in measurement do not have high crest factors. For example, sinewaves have a crest factor of 1.414; triangular waves have CF of 1.73; for an SCR output, the CF varies from 1.414 to 3 as power output varies from 100% to 10%. One of the few waveforms which has high crest factor is noise; however, the crest factor of common noise is 3 or less for 99.7% of the time. The probability of a gaussian noise having a crest factor greater than 4 is 0.01%.

   A zero based pulse train is one of the rare waveforms which can have very high crest factors; such a pulse train with a 1% duty cycle will have a crest factor of ten. Using the high crest factor connection, the LH0091 will respond to signals with crest factor of 10 with typically no more than 0.2% error.

2. **Accuracy.** The accuracy of a converter is in reality its conversion error. Error is the amount by which the actual DC output differs from the theoratical value. It is customary to define error as a sum of a fixed offset term and a percent of reading term. For the LH0091, both the unadjusted and the adjusted total errors are specified; they are 20 mV ±0.5% and 0.5 mV ±0.05% respectively.

3. **Frequency Response.** The frequency response of a computing type RMS converter has an upper and a lower bound; on the low frequency end, it depends on the size of averaging capacitor; on the high frequency end, it depends on internal circuitry. Since this type of converter uses an RC filter for averaging, the RC time constant is critical for low frequency response. The RC time constant should be much greeter (10 times or more) than the period of the lowest frequency component of the signal. For the LH0091, the RC time constant is simply the product of a 10 kΩ resistor and the external capacitor. Low leakage capacitors should be chosen.

4. **Frequency for Specified Adjusted Error.** This is the frequency below which the output will maintain the adjusted accuracy (specified for sinewaves). For the LH0091, the device will maintain the adjusted accuracy to 70 kHz, typically, for a 7 Vrms input.

5. **Frequency for 1% Additional Error.** This is the frequency below which the device will have an additional error of less than 1% of the initial reading (midband). This is also specified for sinewaves. This frequency is typically 200 kHz for a 7 Vrms input with the LH0091.

APPLICATIONS

RMS converters may be used in measurement of virtually any waveform. The examples below are only a few of the many possible applications.

A. Spectrum Analysis

Spectrum analysis is useful in characterizing random phenomena, identifying sources of mechanical vibration and noise. It is also used in characterizing the energy content of a signal. The RMS converter may be used in such an application.

As shown in *Figure 3*, the signal is passed through a tunable bandpass filter, and then it is read by the RMS converter. The output from the RMS converter represents the energy content in the narrow band of frequencies. If this procedure were repeated many times (each time changing the center frequency of the filter) we would have the power spectral density of the signal.

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FIGURE 3. Application of the RMS Converter In Spectrum Analysis

B. Total Harmonic Distortion Meter

A simple and low cost total % harmonic distortion meter is shown in *Figure 4*.

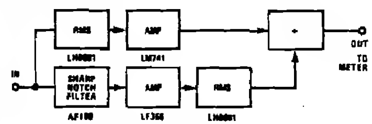

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FIGURE 4. Total Distortion Meter

It is seen that the amplitude of the signal from which the fundamental has been rejected is divided by the amplitude of the composite signal; thus the output is a measure of total harmonic distortion.

C. Noise Meter

A complete noise meter is shown in *Figure 5*. Note that this meter will indicate the total noise within the frequency band of interest. However, if a tunable filter were added, one could plot the noise spectrum of the environment, thus being able to identify the sources of noise.

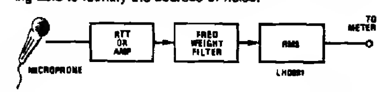

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FIGURE 5. Noise Meter

D. Current Measurement

A current meter capable of measuring complex current waveforms is shown in *Figure 8*. Note that since the RMS converter is used, virtually any current waveform may be measured. Examples of such current waveforms are pulse train, SCR, and noise.

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FIGURE 6. Current Meter

E. DVM AC Interface

Another application of the RMS converter would be an AC interface to a DVM. With such an interface, a DVM may be used to measure complex signals. Since most computing type RMS converters have relatively low input impedance, a buffer should be added as shown in *Figure 7*.

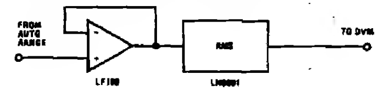

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FIGURE 7. DVM AC Interface

F. Random Vibration and Noise

Random phenomena, such as random vibration and electrical noise, may be described only by such quantities as RMS, power spectral density, and probability distribution of magnitudes.

The spectral density of a wide band random signal is defined to be the mean square value of the signal per unit bandwidth. It is seen that we can obtain a kind of spectral density by dividing the RMS value (band limited) by the square root of the noise bandwidth, where:

$$\text{noise} = E/\sqrt{\Delta f}\ \text{volts/Hz}^{1/2}$$

The result can be interpreted as simply the RMS noise voltage in 1 Hz of bandwidth. Thus wideband electrical noise may be measured as shown in *Figure 8*. If the filter in *Figure 8* is tunable, then it would be possible to plot the spectral density of the signal.

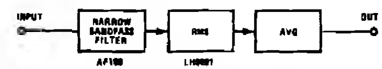

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FIGURE 6. Measurement of Noise

For random mechanical vibrations, an accelerometer and a preamp are added to the ciruct. This is shown in *Figure 9*.

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FIGURE 9. Application of the RMS Converter In Random Vibration

G. Ball Bearing and Other Vibrational Failure Monitor

A very interesting application of the RMS converter is in the monitoring of ball bearing and other vibrational failure. A discussion is given on the ball bearing, but the principle is applicable to any vibrational monitors.

It has been found* that a knowledge of bearing geometry is sufficient to enable the prediction of frequency of fault-induced vibration. There are natural frequency formulas relating directly to bearing geometry. When vibration is generated by impact due to defects, the impact frequencies are usually much lower than the natural frequency of the outer bearing race. Thus the natural frequencies are brought to life. An example of this would be a bell of 200 Hz natural frequency being struck several times a second: the corresponding plot of the oscillation would tend to exhibit 200 Hz and ignore the striking frequency.

It is possible to monitor the fundamental frequency of the outer race. However, it may be necessary to monitor a band of frequencies, depending on the application. If an RMS reading is taken to detect the normal operation level of a new bearing (after a few hours of operation) a safe level may now be set. Thereafter, if the RMS level exceeds the set safe level, an alarm could be triggered. A circuit for such a function is shown in *Figure 10*. If the bandpass filter is tunable, diagnosis of the failure can be performed.

CONCLUSION

In conclusion, it has been found that the RMS converter is a versatile component. Applications range from complex current waveform measurement to ball bearing failure monitor. The examples cited in this note are but a few of the many possible applications.

REFERENCES

Blake and Mitchell, *Vibration and Acoustic Measurement Handbook*, Spartan Books, 1972.

Fieldhouse, *Techniques for Identifying Sources of Nosie & Vibration*, Spectral Dynamics Corp, San Diego, CA, 1969.

Hsu, Hwei P., *Fourier Analysis*, Simon & Schuster, 1970.

Magrab and Blomquest, *The Measurement of Time-Varying Phenomena*, Wiley, 1971.

Oliver, *Electrical Measurement & Instrumentation*, McGraw Hill, 1971.

Pennington, Dale, *Basic Shock and Vibration Theory*, Endevco Corp., San Juan Capistrano, CA, 1966.

"Detection of Ball Bearing Malfunction," *Instrument and Control Systems*, Dec. 1970.

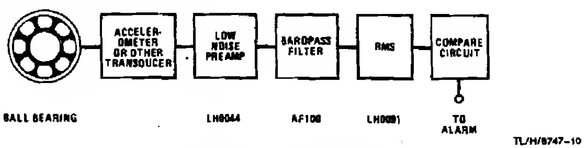

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FIGURE 10. Ball Bearing Failure Monitor

*See *Vibration & Acoustic Measurement Handbook*, Blake & Mitchell, Spartan Books, 1972 and "Detection of Ball Bearing Malfunction," *Inst. & Control*, Dec. 1970.

3-Terminal Regulator is Adjustable

National Semiconductor
Application Note 181

INTRODUCTION

Until now, all of the 3-terminal power IC voltage regulators have a fixed output voltage. In spite of this limitation, their ease of use, low cost, and full on-chip overload protection have generated wide acceptance. Now, with the introduction of the LM117, it is possible to use a single regulator for any output voltage from 1.2V to 37V at 1.5A. Selecting close-tolerance output voltage parts or designing discrete regulators for particular applications is no longer necessary since the output voltage can be adjusted. Further, only one regulator type need be stocked for a wide range of applications. Additionally, an adjustable regulator is more versatile, lending itself to many applications not suitable for fixed output devices.

In addition to adjustability, the new regulator features performance a factor of 10 better than fixed output regulators. Line regulation is 0.01%/V and load regulation is only 0.1%. It is packaged in standard TO-3 transistor packages so that heat sinking is easily accomplished with standard heat sinks. Besides higher performance, overload protection circuitry is improved, increasing reliability.

ADJUSTABLE REGULATOR CIRCUIT

The adjustment of a 3-terminal regulator can be easily understood by referring to *Figure 1*, which shows a functional circuit. An op amp, connected as a unity gain buffer, drives a power Darlington. The op amp and biasing circuitry for the regulator are arranged so that all the quiescent current is delivered to the regulator output (rather than ground) eliminating the need for a separate ground terminal. Further, all the circuitry is designed to operate over the 2V to 40V input to output differential of the regulator.

A 1.2V reference voltage appears inserted between the non-inverting input of the op amp and the adjustment terminal. About 50 μA is needed to bias the reference and this current comes out of the adjustment terminal. In operation, the output of the regulator is the voltage of the adjustment terminal plus 1.2V. If the adjustment terminal is grounded, the device acts as a 1.2V regulator. For higher output voltages, a divider R1 and R2 is connected from the output to ground as is shown in *Figure 2*. The 1.2V reference across resistor R1 forces 5 mA of current to flow. This 5 mA then flows through R2, increasing the voltage at the adjustment terminal and therefore the output voltage. The output voltage is given by:

$$V_{OUT} = 1.2V\left(1 + \frac{R2}{R1}\right) + 50\ \mu A\ R2$$

The 50 μA biasing current is small compared to 5 mA and causes only a small error in actual output voltages. Further, it is extremely well regulated against line voltage or load current changes so that is contributes virtually no error to dynamic regulation. Of course, programming currents other than 5 mA can be used depending upon the application.

Since the regulator is floating, all the quiescent current must be absorbed by the load. With too light of a load, regulation is impaired. Usually the 5 mA programming current is sufficient; however, worst case minimum load for commercial grade parts requires a minimum load of 10 mA. The minimum load current can be compared to the quiescent current of standard regulators.

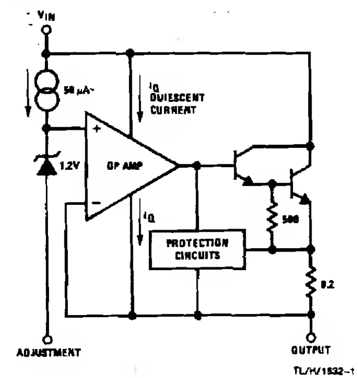

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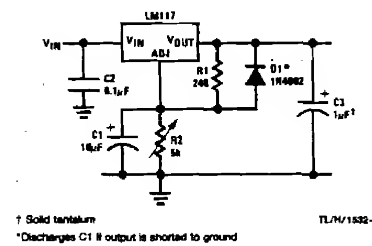
FIGURE 1. Functional Schematic of the LM117



† Solid tantalum

*Discharges C1 if output is shorted to ground

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FIGURE 2. Adjustable Regulator with Improved Ripple Rejection

True rms Detector

National Semiconductor
Linear Brief 25

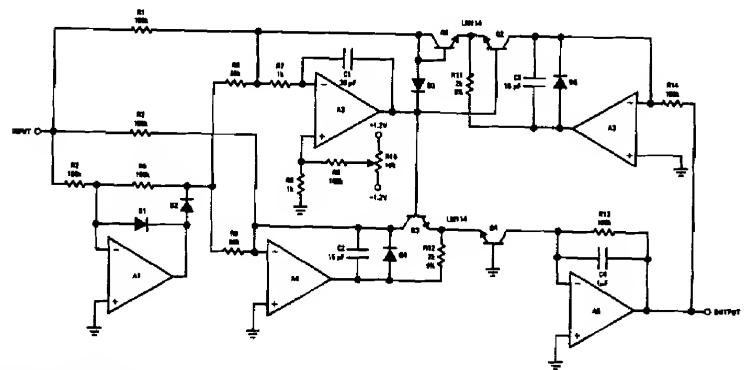
INTRODUCTION

The op amp precision rectifier circuits have greatly eased the problems of AC to DC conversion. It is possible to measure millivolt AC signal with a DC meter with better than 1% accuracy. Inaccuracy due to diode turn-on and nonlinearity is eliminated, and precise rectification of low level signals is obtained.

Once the signal is rectified, it is normally filtered to obtain a smooth DC output. The output is proportional to the average value of the AC input signal, rather than the root mean square. With known input waveforms such as a sine, triangle, or square; this is adequate since there is a known proportionality between rms and average values. However, when the waveform is complex or unknown, a direct readout of the rms value is desirable.

The circuit shown will provide a DC output equal to the rms value of the input. Accuracy is typically 2% for a 20 $V_{p\text{-}p}$ input signal from 50 Hz to 100 kHz, although it's usable to about 500 kHz. The lower frequency is limited by the size of the filter capacitor. Further, since the input is DC coupled, it can provide the true rms equivalent of a DC and AC signal.

Basically, the circuit is a precision absolute value circuit connected to a one-quadrant multiplier/divider. Amplifier A1 is the absolute value amplifier and provides a positive input current to amplifiers A2 and A4 independent of signal polarity. If the input signal is positive, A1's output is clamped at −0.6V, D2 is reverse biased, and no signal flows through R5 and R6. Positive signal current flows through R1 and R2 into the summing junctions of A2 and A4. When the input is negative, an inverted signal appears at the output of A1 (output is taken from D2). This is summed through R5 and R6 with the input signal from R1 and R2. Twice the current flows through R5 and R6 and the net input to A2 and A4 is positive.



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Note 1: All operational amplifiers are LM118.

Note 2: All resistors are 1% unless otherwise specified.

Note 2: All diodes are 1N914.

Note 4: Supply voltage ±15V.

Amplifiers A2 through A5 with transistors Q1 through Q4 form a log multiplier/divider. Since the currents into the op amps are negligible, all the input currents flow through the logging transistors. Assuming the transistors to be matched, the V_{be} of Q4 is:

$$V_{be}(Q4) = V_{be}(Q1) + V_{be}(Q3) - V_{be}(Q2)$$

The V_{be}'s of these transistors are logarithmically proportional to their collector currents so

$$\log(I_{C4}) = \log(I_{C1}) + \log(I_{C3}) - \log(I_{C2})$$

$$\text{or } I_{C4} = \frac{I_{C1} I_{C3}}{I_{C2}}$$

where I_{C1}, I_{C2}, I_{C3}, and I_{C4} are the collector currents of transistors Q1–Q4.

Since I_{C1} equal I_{C3} and is proportional to the input, the square of the input signal is generated. The square of the input appears as the collector current of Q4. Averaging is done by C4, giving a mean square output. The filtered output of Q4 is fed back to Q2 to perform continuous division where the divisor is proportional to the output signal for a true root mean square output.

Due to mismatches in transistors, it is necessary to calibrate the circuit. This is accomplished by feeding a small offset into amplifier A2. A 10V DC input signal is applied, and R10 is adjusted for a 10V DC output. The adjustment of R10 changes the gain of the multiplier by adding or subtracting voltage from the log voltages generated by the transistors. Therefore, both the resistor inaccuracies and V_{be} mismatches are corrected.

For best results, transistors Q1 through Q4 should be matched, have high beta, and be at the same temperature. Since dual transistors are common, good results can be obtained if Q1, Q2 and Q3, Q4 are paired. They should be mounted in close proximity or on a common heat sink, if possible. As a final note, it is necessary to bypass all op amps with 0.1 µF disc capacitors.

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